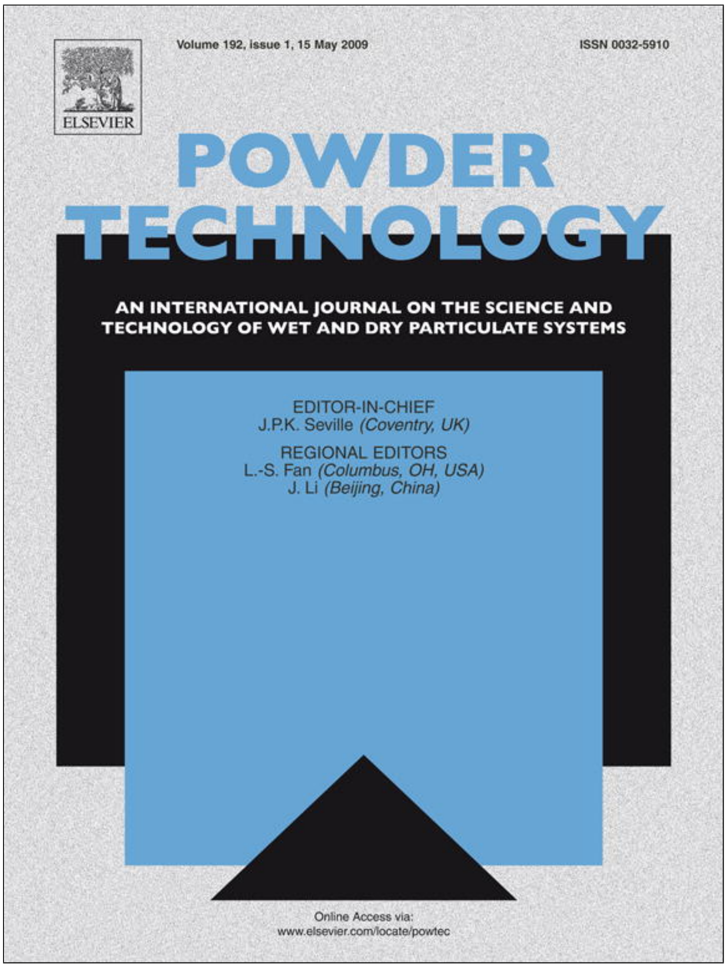
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Comparative study of the mechanical properties of sinterized magnetic alloys applied to electrical machines' core

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ABSTRACT

This paper aims at making a comparative study of some soft magnetic material alloys, which are likely to be used in the construction of rotative electrical machines' core or electrical motors. Therefore, this study focus on the building of massive cores, obtained from the conventional powder metallurgy process, also known as sinterized materials. The mechanical properties of hardness and yield stress are analyzed and compared, resulting in an increase of hardness and yield stress due to the influence of diffusion among the elements utilized in the alloys.

1. Introduction

The magnetic cores of electric motors (stator and rotor), with not many exceptions, are currently built from thin metallic blades (sheet) with thickness less than 1 mm, clustered in sheet packs, later submitted to a thermal treatment. In these sheet packs, the adjacent blades are electrically isolated using substances such as oxides. Magnetic cores involved by coils, where alternating currents flow, create an alternating magnetic flux. That is why these cores can be affected by the action of stray currents, also known as Foucault currents. These currents are responsible for considerable loss of power in the cores. The construction of theses magnetic cores made from electrically isolated steel sheet partially decreases the stray currents, reducing the loss caused by Foucault currents. It is important to mention that, in the construction of cores in conventional motors, the steel must be laminated, treated, die forded in disc-shape, packed and submitted to thermal treatment processes and electrical isolation by oxidation [1,2].

However, when the powder metallurgy processes are used, it is possible to build these cores in only one massive block, with a high magnetic permeability (which is an aspect of magnetic steels) and a high electrical resistivity, thus reducing the stray currents [3,4]. The application of this process in constructing electrical motors cores may result in motors bearing several advantages on those with conventional cores. Some of these advantages are: (a) less stages in the core constructing process and less energy use; (b) stator and rotor with greater electrical resistivity and less affected by stray currents; (c) lighter motors, less use of energy and higher efficiency and (d) cheaper raw materials.

When referring to the mechanical aspects, the electric machines in use are submitted to charges which, besides having an opposite resistive turning moment, may result in vibration in the machine-charge system. Therefore, the studied alloys must present the necessary ductility, hardness and mechanical vibration resistance to tolerate the efforts that come from the magnetic fields in the core, as well as to resist the vibrations that are originated when the machine is working.

This study analyzes the sinterized magnetic alloys that can be possibly utilized in the construction of massive cores in rotative electrical machines or electrical motors, evaluating the behavior of mechanical properties such as Brinell hardness and yield stress.

2. Powder metallurgy

There are several production technologies that are used to obtain magnetic materials through metallurgic processes. Among these, it is important to mention casting and powder metallurgy, which is a more recent metallurgy area [5–7].

The four basic stages of the powder metallurgy are: powder manufacture, powder mixture, pressing and sintering. Sometimes, grinding is needed as a fifth step. In powder metallurgy, the powders, after being mixed, are compacted in rigid dies, where they acquire the

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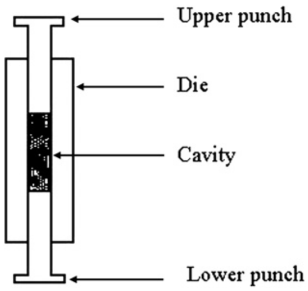

Fig. 1. Double-acting compaction dye for pressing magnetic materials.

Fig. 2. Matrix to obtain the samples.

form of the cavity of the die. After that, the powders are put in sinterizing furnaces, to acquire consistency and mechanical strength. It is crucial to state that powders with different chemical natures are easily obtained by homogeneous mixtures [5–7].

Fig. 1 shows schematically double-acting compaction die, used to press magnetic material powder:

3. Sample preparation

The steel powder samples used in this work are provided by Höganas do Brasil Ltda. To evaluate the mechanical properties, a die for making the samples in the form of a cylinder was produced. The samples were used to evaluate mechanical properties such as Brinell hardness and yield stress. The sample preparation begins with the mixing process, using a conventional mixer in a shape of cone with balls.

The alloys are prepared mixtures of powdered metal of pure iron with P, S, Ni and Mo and iron-based prealloyed powder with P and Ni.

Fig. 3. Sample used to characterize the mechanical properties.

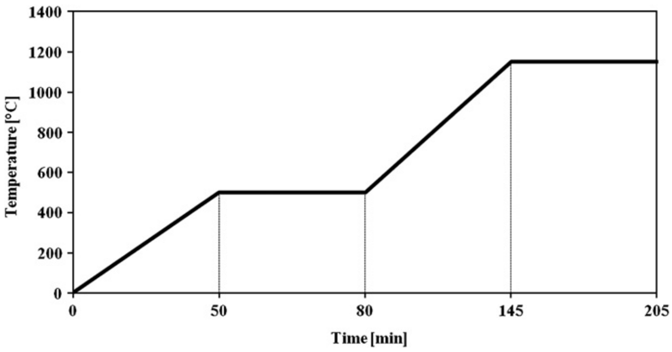

Fig. 4. Sintering curve as a function of the time.

3.1. Compaction

The sample compaction was held in a universal mechanical testing machine of the brand KRATOS, with a capacity of 100 kN (1000 kgf). This press has a censored ton indication which comes from a load cell connected at the top of the press. The samples were compressed to a pressure of 600 MPa, where 1 Pa = 1 N/m^2. Considering that 1 t is approximately 10,000 N, the result is the following:

$$600\text{MPa} = 6\times10^8 \frac{N}{m^2} = 6\times10^4 \frac{\text{ton}}{m^2} = 6\frac{\text{ton}}{\text{cm}^2}$$

Considering the area of cross section of the matrix, 41 mm^2, it resulted in a compaction pressure of 21.88 kN. The Figs. 2 and 3 show, respectively, the picture of the matrix and the sample.

3.2. Sintering

The sintering was carried out in a muffle furnace, within a controlled atmosphere. The sintering temperature was around 1.150 °C, and the sintering time was 60 min. The heating rate was approximately 10 °C/min, and all the parts were kept in the furnace for slow cooling to room temperature. Before the sintering temperature is reached, the parts were maintained during 30 min at 500 °C to burn lubricant (zinc stearate). Fig. 4 presents the heating curve used in this work as a function of the time.

3.3. Finishing and density of samples

Due to the relatively small average size and the pieces complex formats, it requires special procedures and precautions, different from casting and wrought. Considering the inherent properties of the piece, it demands special considerations of all secondary operations, mainly cleaning and chipping. The measures of density were made at room temperature by the relationship between mass and volume of the

Table 1
Sintered samples density

Sample	Sintered alloy	Compressed density [g/cm³]	Sintered density [g/cm³]
01	Pure iron	6,87	6,87
02	Fe-0,45%P	6,79	7,06
03	Fe-0,8%P	6,74	6,99
04	Fe-1%P	6,84	6,47
05	Fe-3%Si	6,49	6,30
06	Fe-50%Ni	6,85	7,02
07	Fe-81%Ni-2%Mo	6,79	8,04
08	Fe-6%Si	6,08	5,64
09	Fe-50%Ni (prealloyed)	7,02	7,06

Table 2
Sintered samples Brinell hardness

Sample	Sintered alloy	Brinell hardness [BH]	Difference [%]
01	Pure iron	64,5	0,00
02	Fe-0,45%P	98,0	51,94
03	Fe-0,8%P	124,3	92,71
04	Fe-1%P	138,3	114,42
05	Fe-3%Si	73,2	13,49
06	Fe-50%Ni	101,0	56,59
07	Fe-81%Ni-2%Mo	104,7	62,33
08	Fe-6%Si	101,9	57,98
09	Fe-50%Ni (prealloyed)	76,6	18,76

Table 3
Sintered alloys' yield stress

Sample	Sintered alloy	Load [N]	σ_e [N/mm^2]	Difference [%]
01	Pure iron	5488	137,10	0,00
02	Fe-0,45%P	4959	123,88	−9,65
03	Fe-0,8%P	6713	167,70	22,30
04	Fe-1%P	5782	144,44	5,72
05	Fe-3%Si	6272	156,68	14,30
06	Fe-50%Ni	6468	161,58	17,87
07	Fe-81%Ni-2%Mo	4704	117,51	−14,30
08	Fe-6%Si	6762	168,92	23,23
09	Fe-50%Ni (prealloyed)	5782	144,44	5,65

samples, and were calculated by samples dimensional measures. Table 1 shows the relationship of the studied sintered alloys and compressed density and afterwards sintered.

4. Mechanical properties

Besides the electromagnetic properties to be used in core of electric motors, the sintered alloys should be analyzed according to their mechanical properties, hardness and yield stress due to the need of tolerating the efforts generated when the machine is operating. The hardness tests were performed by measuring Brinell hardness, and the test parameters are: sphere type penetrator of 2,5 mm diameter and load of 31 N. Table 2 shows the values of Brinell hardness of the studied sintered alloys, when Sample 1 (pure iron) was used as a reference. Fig. 5 shows a comparison between the values of hardness of the sintered alloys studied.

The test to obtain the Yield Stress (σ_e) was performed in the same machine, the universal mechanical testing machine KRATOS used for the compression of the samples. The yield stress is calculated according to:

$$\sigma_e = \frac{F}{A}.$$

Where

σ_e	Yield stress [N/mm^2]
F	Compression load [N]
A	Surface area under compression (40,03 mm^2)

Considering that these tests are performed at a speed of 3 mm/min, the following results are obtained according to Table 3 for the several of the studied sintered alloys, when Reference Sample 1 was taken as a reference and it was compared in percentage with the other sintered alloys.

Fig. 6 shows a comparison chart of yield stress values of the studied sintered alloys where the pure iron sintered (Sample 1) was used as reference.

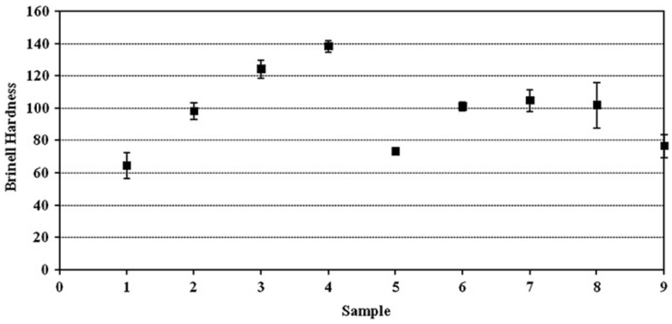

Fig. 5. Brinell hardness values of the sintered alloys.

The yield stress determination is only used for comparative purposes among the sintered alloys, because no data were obtained from deformation in the course of the test.

5. Discussion

Whereas the samples tested have electromagnetic properties compatible for application as core massive electrical machines. These properties are observed in the Table 4 that shows the physical properties of the sintered alloys previously obtained in this work compared with pure iron [8].

According to the results of Table 4, for the application of these alloys as magnetic core, the samples were characterized in terms of their mechanical properties looking to assign these materials to use as a basis for making these massive core electrical machines.

The compaction pressure has great influence on the density of the material, that is why the sintered alloys studied have variations in density after compressed and sintered. Their densities were verified in purely compacted and sintered stages, and, in general, there was virtually no variation in dimensional samples after sintering. Density is the most important parameter in this context. As the density of powder metallurgical parts increase, physical and mechanical properties improve and at a near-full density the properties are comparable with their wrought counterparts. It is therefore realized that powder metallurgy substitution can only be possible by proper densification at a reasonably low cost [9].

At a higher sintered density, generally above 80% TD (theoretical density), the formation of interconnected pores and pore isolation occur, marking the intermediate and final stages, respectively. Sintering protocols, namely firing time and temperature, are among the factors that control the progression through these stages. It is clear that in many applications it is desirable to sinter powder materials through all three stages to full density, such that optimum strength is achieved. In some applications, however, full sintering is not required or may even be undesirable from the point of view of property control or economics [10].

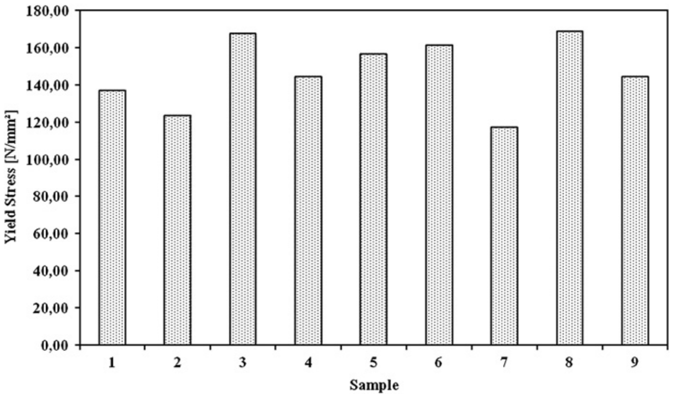

Fig. 6. Comparative graphic of yield stress.

Table 4
Sintered alloys electromagnetic properties

Composition	B_{max} [T]	B_{max} [kG]	B_r [T]	B_r [kG]	H_c [A/m]	H_c [Oe]	μ_r	ρ_e [μΩ.m]
Pure iron	1,14	11,40	0,96	9,60	131	1,65	2.900	0,14
	1,36	13,60	1,18	11,80	127	1,60	3.700	0,12
	1,47	14,70	1,29	12,90	119	1,50	4.700	0,11
Fe-0,45%P	1,70	17,00	1,24	12,39	63,50	0,82	7.178	0,20
Fe-0,8%P	1,10	11,01	0,72	7,19	95,25	1,23	4.847	0,22
Fe-1%P	1,55	15,50	0,79	7,91	67,31	0,87	4.958	0,24
Fe-3%Si	1,15	11,56	1,31	13,10	114,30	1,48	4.255	0,46
Fe-50%Ni	0,91	9,11	1,18	11,80	157,48	2,05	2.442	0,65
Fe-81%Ni-2%Mo	0,73	7,34	0,63	6,25	74,93	0,97	3.626	0,22
Fe-6%Si	1,13	11,28	0,71	7,08	97,79	1,27	2.923	1,37
Fe-50%Ni (prealloyed)	1,17	11,70	0,38	3,78	38,10	0,50	4.662	0,58

The increase in hardness of alloys, when compared to Sample 1, is related to the formation of solid solution, coupled to a microstructure densification. The Phosphorous, if not added to levels above 1%, increases the hardness and yield point forming, together with the iron, a homogeneous phase. The nickel addition increases the yield point and its influence is enhanced with increased diffusion in solid solution, that is, it remains in solid state during sintering and diffuses only partially into iron, contributing to a heterogeneous microstructure where nickel is presented predominantly at the periphery of the pores [11–14]. This also promotes an increase of elastic properties through the retention of ductile austenite. However, with the molybdenum addition, there is a decrease in the yield point, as in the case of Sample 7, due to the possible carbides formation and these are not dissolved in the formed matrix.

These described behaviors may not follow the logic of mixtures according to the results of tests by the fact that it has the influence of the compacting parameters and testing, and that the number of samples tested, mainly in obtaining the yield stress, where in this case there is a need for a greater amount of testing.

Sintered materials are typically characterized by residual porosity after sintering, which is quite detrimental to the mechanical properties of these materials. The nature of the porosity is controlled by several processing variables such as green density, sintering temperature and time, alloying additions, and particle size of the initial powders. In particular, the fraction, size, distribution, and morphology of the porosity have a profound impact on mechanical behavior [11–17].

6. Conclusions

According to the experimental results in this study, the following conclusions may be discussed:

- Compared to the sample of pure iron, there was an increase of Hardness for all samples studied, which is related to the formation of solid solution coupled to a microstructure densification.
- Based on the measurements of yield stress, the samples 3, 6 and 8 show higher values as a function of pure iron, because of the likely formation of homogeneous phase according to the largest diffusion in solid solution by the elements used in the preparation of samples.
- For the use in the electrical machines, it is possible to use these materials as the results, listing density and mechanical properties, are satisfactory in comparison to the material usually used in the conventional process in the manufacture of cores by rolled plates.

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